Follow-on Studies Using the Voyager Spacecraft Thermal Model

ICES Paper 2019-377

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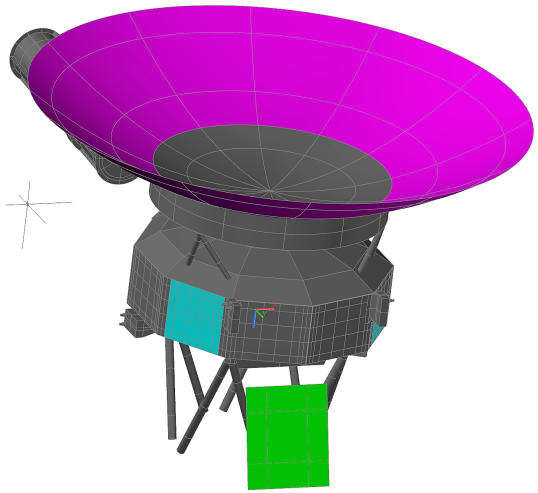


U.S. Government Sponsorship Acknowledged

Agenda

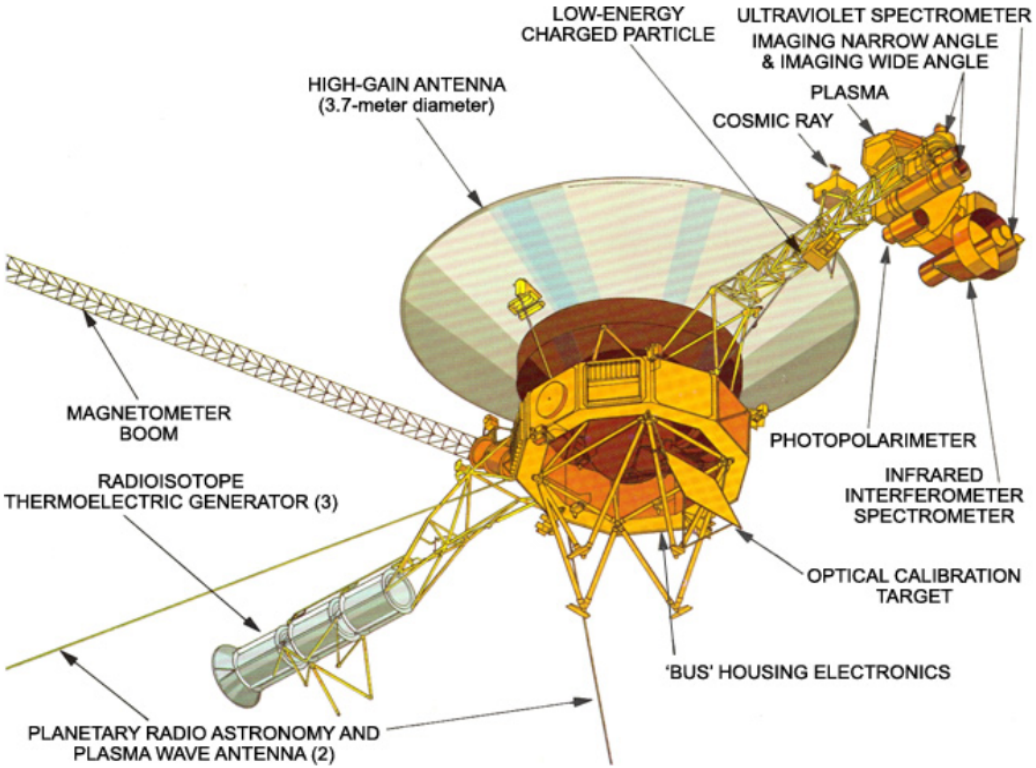
- Introduction
- Voyager Mission Overview
- Propulsion Subsystem
- Spacecraft Thermal Model
- Minimum Allowable Flight Temperature (AFT) for Propellant
- December 2018 Thermal Anomaly
- Voyager 2 Power State Change Decision
- Conclusions

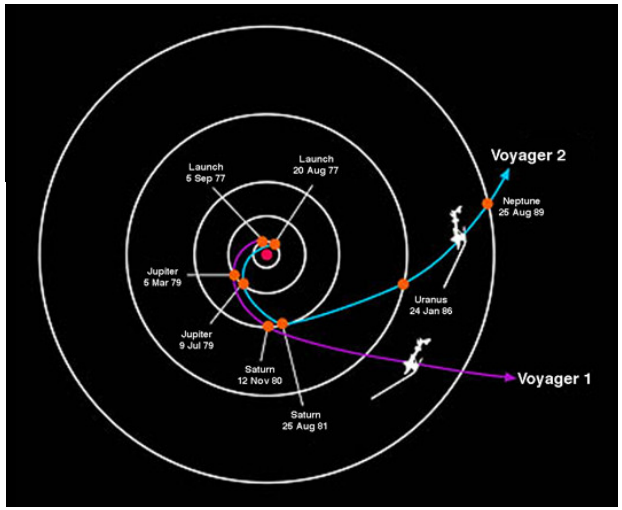
Introduction

- Launched in 1977, the 42-year old Voyager spacecraft are running out of power and propellant temperatures continue to decrease.
- To preserve the mission and continue science, hard choices need to be made.
- What temperature limit should be set to keep the propellant lines from freezing?
- What are the options for managing power and thermal margins?
- This paper tells the story of how the Voyager team is answering these questions.

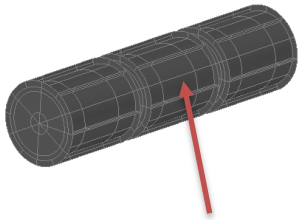
Mission Overview

The Voyager spacecraft, each carrying 10 science instruments were launched 42 years ago to explore the outer planets and are now in interstellar space.

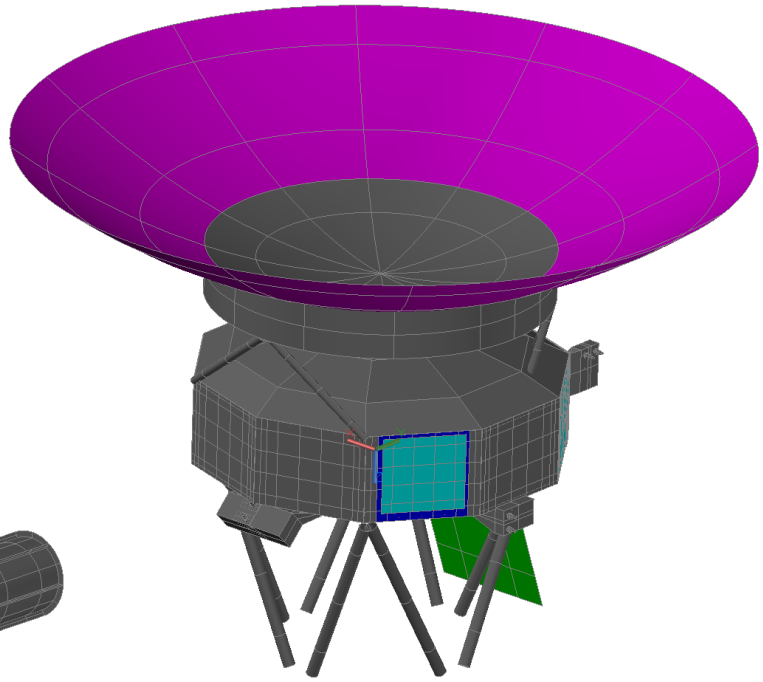




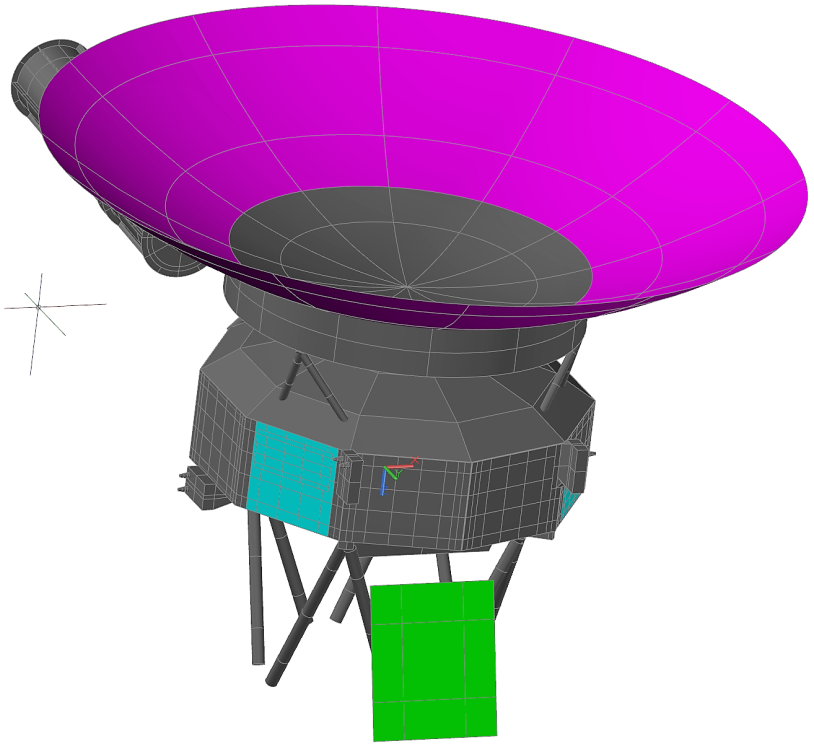
Spacecraft Thermal Model



RTG outer case
T = 204°C



-X View

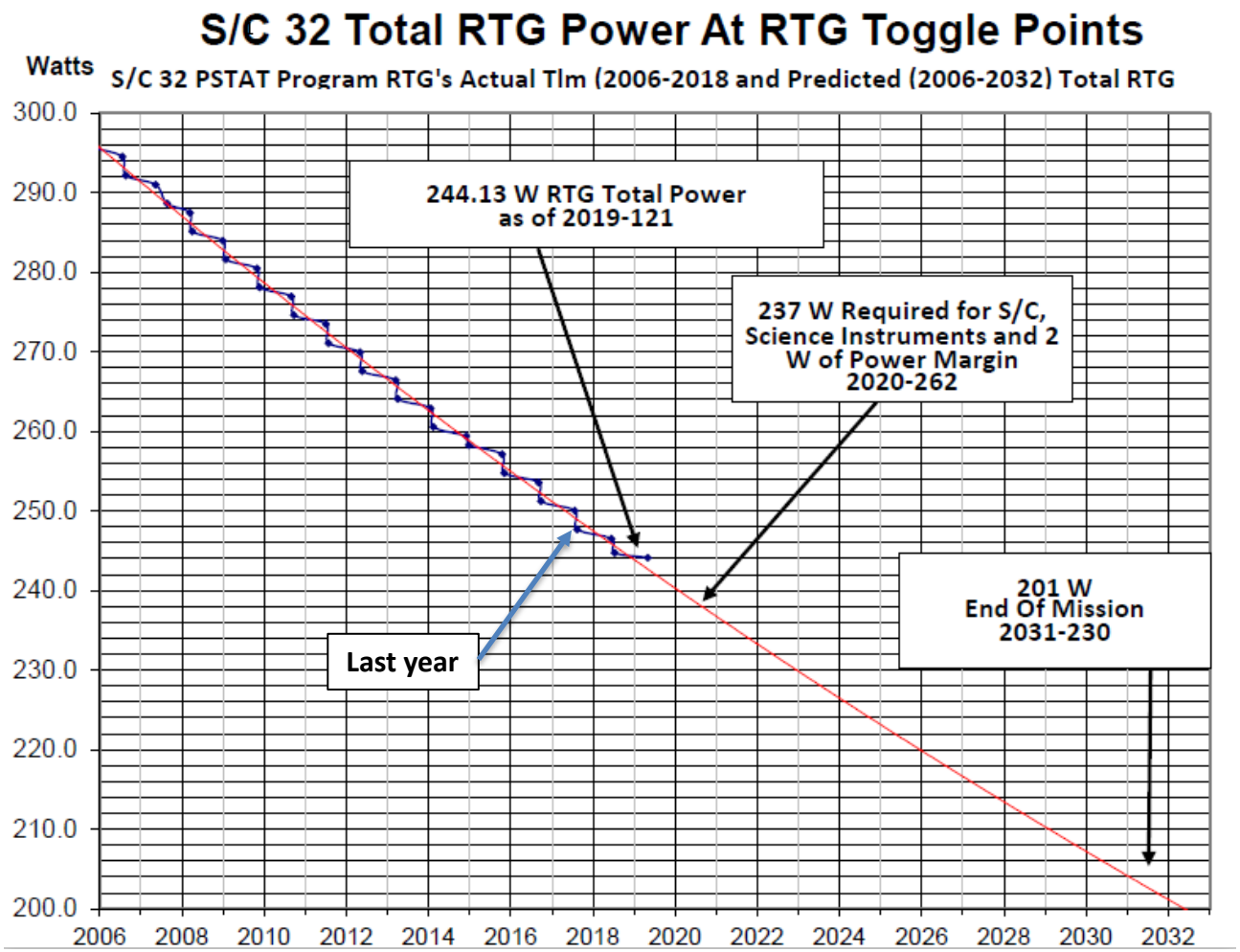


+X View

1,177 surfaces and thin-shell elements
4,543 nodes

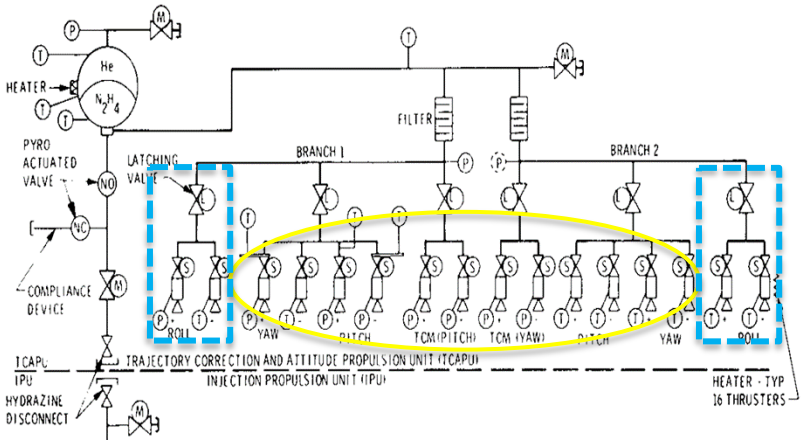
Still Running Out of Power…

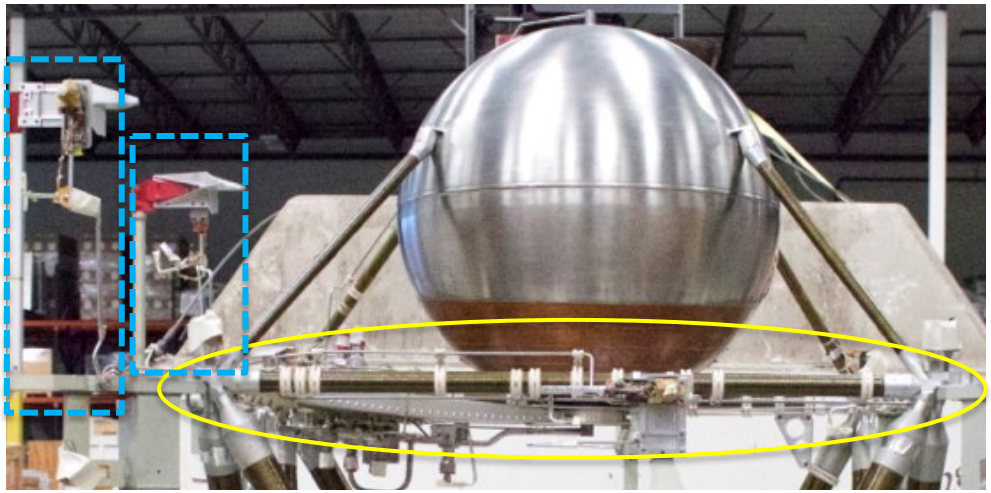
- Each spacecraft carries three Radioisotope Thermoelectric Generators (RTGs).
- These power all of the on-board science and engineering functions.
- As the graph shows, by Fall of 2020 the Voyager 2 (S/C 32) power margin will have dropped to 2 W.
- For the mission to continue, some function(s) must be turned off before the power margin gets that low.
- PSTAT is software used to calculate RTG power from telemetry.



Propulsion Subsystem Thermal Design

- Fuel Tank positioned at center of spacecraft bus.
- Blow-down monopropellant (hydrazine) flows through stainless steel lines, filters and valves to reach each of the 16 thruster/valve assemblies (T/VAs).





- Propellant lines mostly routed in-plane, directly beneath spacecraft bus.
- Four roll thruster lines are the coldest.
- Only 6 temperatures sensors on propulsion subsystem hardware.
- Derived channels used to estimate temperatures near thruster inlets.

Minimum Allowable Flight Temperature (AFT) for Propellant

- Propellant Freezing Temperature
  - Assumed to be 1.4°C, based on:
    - Water content ~0.8%
      - Reference 2 indicates pure hydrazine freezing point as 2.0°C
      - Cassini measured 0.8% water content in mid-1990's
      - Voyager initially produced ultrapure hydrazine, but then added water back in since their experience base with these thrusters was with more water content
      - Unable to find records of actual measurement of Voyager propellant water content
      - Decreases freezing point by 0.7°C
    - Tank pressure ~190 psia
      - Raises freezing point by 0.1°C

Minimum Allowable Flight Temperature (AFT) for Propellant

- "Known" uncertainties in temperature measurements

Error Source	
Lead Wire Error	±0.2°C
Digital Number Quantization	0.7°C/DN
PRT Accuracy	±0.1°C
PRT Mounting Error	±0.05°C
Uncertainty in Derived Channels	±1.1°C
RSS Measurement Uncertainty	±1.3°C

- Unknown Uncertainties: includes additional 1°C
  - Avionics conversion of the analog single to digital
  - Current source variability with temperature.
- Recommended minimum **AFT = 3.7°C**

December 2018 Voyager 2 Thermal Anomaly

- Command file error resulted in Bay 1/Bay 9 Heater (24.2 W) not being turned back on following magnetometer calibration (MAGROL) maneuver.
  - Coldest propellant line (+Roll) reached a steady-state temperature of 1.15°C before commands could be sent to restore baseline power state (~66 hours after error was noticed).
  - AACS did not detect any anomalous thruster performance.
  - Did propellant freeze, then thaw?
  - Are our derived telemetry channels inaccurate?
  - Did we just get lucky?
- Discovered that propellant line heaters (3.1 W) had been ON (were believed to be OFF prior to anomaly).

Attempted Recovery #1

- SURPRISE!
- Voyager 2 propellant line heaters were already on
- Likely SINCE BEFORE LAUNCH

- No one knew about it, until December 2018

- How could this have happened?!

Voyager 2 Power State Change Decision

- Current power margin = 3.7 W
- Current thermal margin = -0.8°C
  - +Roll line = 3.3°C
  - -Roll line = 2.9°C
- DSN Downtime
  - DSS-43 (Canberra 70 m) will be down from Feb. – Dec. 2020
  - No uplink/commanding possible for Voyager 2
- Options:
  - Turn off instrument heaters and/or instruments
  - Reconfigure bus heaters to improve propellant line temperature distribution
- Thermal model used to assess all options

Voyager 2 Power State Change Decision (cont.)

The Voyager project decided that best course of action in order to pursue the best science mission on Voyager 2 is to begin turning off instrument heaters.

- The CRS heater was turned off June 26.

Remaining science goals will be re-assessed as power continues to drop against the risks associated with the known power switch issue.

Note: Voyager 1 will have similar mission trades in the 2021 timeframe.

Conclusions

- Propellant minimum AFT--*not a traditional AFT*
- Regularly check for hydrazine freezing
    1. Daily/regular downlink assessment operations.
       -Monitor temperatures and thruster performance.
    2. Prevent hydrazine from freezing proactively.
    3. Plan for nominal hydrazine cooling.
    4. Unexpected rapid hydrazine cooling contingency plan.

Acknowledgements

The authors would like to acknowledge the following people for their contributions to this effort:

- Suzanne Dodd, JPL, Voyager Project Manager
- Virgil Mireles, JPL, Section Manager, Propulsion, Thermal and Materials Section (353)
- Fernando Peralta, JPL, Voyager Mission Operations Engineer

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.